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A model for a borehole heat exchanger working with CO_2

Rita Mastrullo[a]*, Alfonso W Mauro[a], Laura Menna[a], Giuseppe P Vanoli[b]

[a] *Università degli Studi di Napoli Federico II, Dipartimento di Ingegneria Industriale - Sezione ETEC, p.le V. Tecchio 80, 80125 Napoli, Italy*
[b] *Università degli Studi del Sannio, DING, corso Garibaldi 107, 82100 Benevento, Italy*

Abstract

Ground source heat pumps are a valid technology for heating and cooling in residential application, since they allow to have a stable temperature of the heat source/sink by means of ground heat exchangers, generally named as Boreholes. In particular, U-pipe heat exchangers are interesting when working with two-phase fluids, especially during the heating season, when natural circulation might occur. This work presents the model of a borehole heat exchanger working with carbon dioxide as secondary fluid in a U-pipe loop. A closed system of equations is introduced with appropriate correlations for heat transfer and pressure drops, accounting for transient heat conduction due to ground temperature variation. Maps of performance varying the main operating parameters are presented and discussed, showing the potential of the model as tool for sensitivity analysis and as sub-model to find the matching between the heat pump and the borehole heat exchanger.

Keywords:Borehole Heat Exchanger; U-pipe; Carbon Dioxide; Two-phase flow.

1. Introduction

Ground Source Heat Pumps (GHSP) are a valid and well established technology for heating and cooling in residential applications, allowing to use the ground as energy source/sink with the possibility of being built virtually in any location. The GHSP is constituted by a heat pump unit with the evaporator coupled to a Borehole Heat Exchanger (BHE), that is, a probe in the ground where a secondary fluid circulates while exchanging heat with the surroundings.

* Corresponding author. Tel.: +39-081-7682297; fax.: +39-081-2390364.
E-mail address: rita.mastrullo@unina.it

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Nomenclature

D	Diameter [m]
f	Friction factor
g	Gravitational acceleration [m/s^2]
G	Mass flux [kg/m^2·s]
H	Height [m]
i	Specific enthalpy [J/kg]
k	Thermal conductivity [W/m·K]
$\dot{m}$	Mass flow rate [kg/s]
P	Pressure [kPa]
$\dot{q}$	Heat flux per unit length [W/m]
$\dot{Q}$	Heat power [W]
R	Thermal resistance [m·K/W]
T	Temperature [K]
w	Velocity [m/s]
x	Quality

Greek symbols

α	Thermal diffusivity [m^2/s]
δ	Thickness [m]
∂, Δ	Differential
ε	Void fraction
ρ	Density [kg/m^3]

Subscripts

b	borehole
D	related to fluid in the downcomer
EV	evaporator
f	frictional
g	grout
gr	gravitational
IN	inlet
L	liquid
mom	momentum
OUT	outlet
p	pipe
R	related to the fluid in the riser
s	soil
SAT	saturation
SUB	sub-cooling
V	vapor

The secondary fluid, then, exchanges heat in the evaporator of the heat pump, allowing to use the ground as energy source. In the case of reversible heat pump, the ground becomes an energy sink where the secondary fluid release heat and then it vaporize in the condenser of the heat pump.

The most common configuration for a single BHE is the U-pipe loop, where the secondary fluid flows downwards in the downcomer pipe and then upwards in the riser one.

The vertical configuration, although more complicated in terms of installation with respect to the horizontal one, has great advantages in terms of space and of the disposition of the BHEs (series or parallel configurations). Due to the length of the tubes into the ground to reach the appropriate and stable temperature desired, the pressure drop for single-phase flow and, hence, the power required for pumping the fluid are relevant. With two-phase flows, the mass flow rate is reduced due to the possibility of using the heat of vaporization; moreover, the rising of the fluid benefits of the buoyancy forces that reduce the total pressure drop between the inlet and the outlet, allowing, through an appropriate design of the borehole length and diameter, to work with natural circulation.

Therefore, during the last few years, BHEs based on natural circulation have been investigated [1-5]. In these systems, the circulation of the fluid happens without a pump, with the liquid phase flowing in an adiabatic downcomer pipe thanks to gravity and then flowing in the riser pipe while exchanging heat with the ground; the fluid rises thanks to density differences due to evaporation, saving energy for the pumping and, thus, increasing the total performance of the GSHP. In this kind of system, natural circulation is guaranteed when the pressure drop between inlet and outlet is negative, thanks to the major effect of the buoyancy in the rising from the ground. Therefore, the design requirements of a BHE in natural circulation with a two-phase fluid are a mass flow rate and an outlet vapor quality that give a pressure drop and a heat capacity transferred by the ground in the BHE equal to the pressure drop heat capacity required by the evaporator of the GSHP, respectively.

As concerns the choice of the secondary fluid, as reported by previous studies [1-3], the use of CO_2 for GSHP resulted to have great advantages, since there is no contamination of the ground/groundwater in case of leakage. Moreover, CO_2 is non-flammable, non-explosive, relatively non-toxic. Also, it has been shown that CO_2 has very good heat transfer performance during flow boiling in both vertical and horizontal configurations [6-9]. Furthermore, the typical temperatures of CO_2 inside the BHE are around 0°C, thus near the critical point (31°C/74 bar), with high vapor density that, in turns, leads to a higher volumetric refrigeration capacity than other refrigerants, but with lower density variations of the fluid during evaporation and lower buoyancy effect. Therefore, the employment of carbon dioxide in vertical BHEs is particularly appealing for this kind of application due to advantages in environmental and safety, but major attention is required for an appropriate design.

Indeed, there are some disadvantages: in particular, the initial cost is high and, in the case of natural convection, the system can be employed only in heating mode, since the heat flow direction from the bottom to the top of the riser is determined by nature and requires the evaporation of the fluid. Therefore, several efforts have been made in order to optimize these systems, for example varying the pipes configuration an borehole materials [2] and trying to optimize the borehole configuration.

In the field of experimental analysis, Acuna et al [3] investigated the performance of a thermosyphon BHE working with CO_2 in a 70 m deep groundwater filled borehole. Their results show that there is a significant change in temperature profile in the riser that occurs from the GHSP start up to the following operating period. Indeed, there is a decrease in temperature levels due to heat extraction from the ground with the time. Therefore, the analysis of performance of a BHE should take into account for transient heat exchange in ground region around the borehole.

Due to the particular thermodynamic properties of CO_2, to the configuration of the system and to the difficulties related to its installation, it is important to have an accurate design of the system that guarantees a correct balancing when working with the GSHP and optimize the whole system performances.

To this aim, a useful tool is represented by a mathematical model that is able to describe the performance of the system with varying the operating conditions and the borehole geometry, such as fluid inlet conditions and flow rate, ground temperature, ground thermal properties, borehole filling material thermal properties, borehole diameter and height, downcomer and riser diameter and thermal properties.

In this work, the development of a mathematical model of a vertical U-pipe Borehole Heat Exchanger working with CO_2 as heat carrier fluid is presented, taking into account for the pressure drop calculation along the downcomer and the riser and for the transient heat exchange with the ground in the riser tube, with an appropriate selection of prediction methods. In the following the description of the model and a sensitivity analysis to show its potential use are presented.

2. Development of the model

The model developed in this work is a one-dimensional model along the borehole axis developed in quasi-steady state; the temperature and pressure of the fluid along the flow axis are evaluated in hourly simulations by updating the borehole wall temperature, T_b, with respect to the undisturbed soil temperature, T_s, using the cylindrical heat source solution [10,11] to predict transient heat transfer from the borehole boundary to the undisturbed ground. The model is based on further assumptions:

- perfectly insulated downcomer;
- negligible pressure drop in the U-bend;
- undisturbed soil temperature constant along the borehole length;
- uniform borehole wall temperature along the borehole perimeter.

A cross section of the borehole is shown in Fig. 1(a), whereas the detail of the frontal section of the downcomer and riser pipe where the fluid flows is shown in Fig. 1(b).

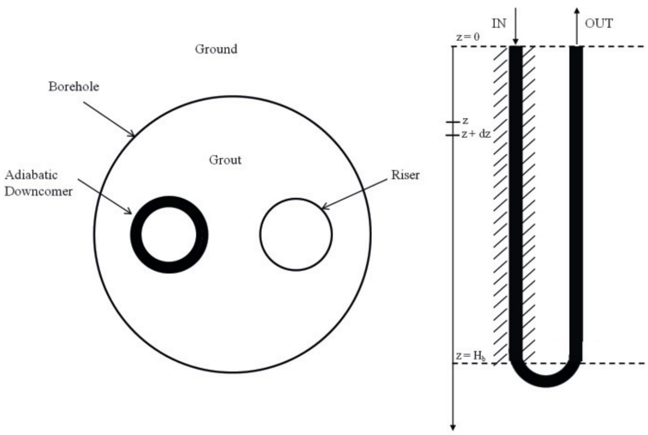

Fig 1. (a) borehole cross section, (b) insight of the borehole frontal section

The downcomer mass, energy and momentum balances in an elemental length dz are, respectively:

$$\frac{\partial \dot{m}}{\partial z} = 0 \tag{1}$$

$$\dot{m} \cdot \frac{\partial (i_D - g \cdot z)}{\partial z} = 0 \tag{2}$$

$$\frac{\partial P_D}{\partial z} = \left.\frac{\partial P}{\partial z}\right|_{gr} - \left.\frac{\partial P}{\partial z}\right|_{f} \tag{3}$$

The gravitational and frictional pressure are evaluated as:

$$\left.\frac{\partial P}{\partial z}\right|_{gr} = \rho_L \cdot g \tag{4}$$

$$\left.\frac{\partial P}{\partial z}\right|_{f} = f_D \cdot \frac{\rho_L \cdot w_D^2}{2 \cdot D_p} \tag{5}$$

with friction factor f_D evaluated according to Schmidt correlation for laminar flow (Eq. 6) and to Blasius formula for turbulent flow [12].

As regards model for the riser, it takes into account for the heat exchange with the surrounding borehole filling material; the riser inlet conditions are generally sub-cooled liquid conditions, therefore, until fluid pressure in the riser, P_R, is lower than saturation pressure at the corresponding fluid temperature, T_R, the energy and momentum balance are:

$$\dot{m} \cdot \frac{\partial(i_R + g \cdot z)}{\partial z} = \dot{q} \tag{6}$$

$$\frac{\partial P_R}{\partial z} = -\left.\frac{\partial P}{\partial z}\right|_{gr} - \left.\frac{\partial P}{\partial z}\right|_{f} \tag{7}$$

the equations for gravitational and frictional pressure drop are the same as reported in the downcomer section (Eq. 4 and Eq. 5, respectively).

The heat flux per unit length is evaluated as:

$$\dot{q} = \frac{T_b - T_R}{R_b} \tag{8}$$

The equivalent borehole thermal resistance per unit length from the borehole wall to the fluid, R_b, accounts for the resistance in the borehole filling material (grout), R_g, and in the pipe, R_p:

$$R_b = R_g + R_p / 2 \tag{9}$$

The grout thermal resistance, R_g, is evaluated according to Shonder and Beck [13]; the pipe thermal resistance considers the series of conductive resistance in the pipe and of convective resistance in the fluid, with the convective heat transfer coefficient evaluated according to Dittus-Boelter correlation [14] in the case of sub-cooled liquid.

The borehole wall temperature, T_b, is determined by solving the transient heat conduction problem in the ground, by considering the solution of Ingersoll et al [10] at the work of Carslaw and Jaeger [11], to the transient heat transfer from a cylinder embedded in an infinite homogeneous medium. The equations are reported in Bernier [15].

When $P_R = P_{SAT}(T_R)$, the sub-cooled liquid length is finished and evaporation starts, therefore, the balances are developed in the case of two-phase flow considering also the kinetic term in the energy balance and the momentum pressure drop in the momentum balance:

$$\dot{m} \cdot \frac{\partial(i_R + g \cdot z + w^2/2)}{\partial z} = \dot{q} \tag{10}$$

$$\frac{\partial P_R}{\partial z} = -\left.\frac{\partial P}{\partial z}\right|_{gr} - \left.\frac{\partial P}{\partial z}\right|_{f} - \left.\frac{\partial P}{\partial z}\right|_{mom} \tag{11}$$

In the two-phase region, the convective heat transfer coefficient for the evaluation of the pipe resistance is evaluated according to Gungor-Winterton correlation [16] that was reported to have a good agreement with experimental data of CO_2 evaporation in vertical pipe [9].

In this case, the gravitational pressure drop was evaluated according to Eq. (4), considering the two-phase density ρ_R in place of the liquid density, evaluated accordingly to the homogeneous two-phase flow model:

$$\rho_R = \rho_V \cdot \varepsilon + \rho_L \cdot (1 - \varepsilon) \tag{12}$$

The void fraction ε was evaluated according to the Steiner version of Rouhani-Axelsson model [17].

The momentum pressure drop term in Eq. 11 was evaluated as:

$$\left.\frac{\partial P}{\partial z}\right|_{mom} = G^2 \left\{ \left[\frac{(1-x)^2}{\rho_L \cdot (1-\varepsilon)} + \frac{x^2}{\rho_V \cdot \varepsilon} \right]_{z+dz} - \left[\frac{(1-x)^2}{\rho_L \cdot (1-\varepsilon)} + \frac{x^2}{\rho_V \cdot \varepsilon} \right]_{z} \right\} \tag{13}$$

where G is the mass flux (mass flow rate per unit area) and x is the quality.

The frictional pressure drop term was evaluated according to Muller-Steinhagen and Heck correlation [18].

It is worth underlining that the trend of the BHE performance with time is of primary importance when the model is intended to be coupled to a ground source heat pump, since it will allow to account for load variations and for ground saturation if the system is operated for a high number of hours or if a multi-BHE system is investigated.

3. Results

In this section, the results obtained with the model are reported, analyzing the effect of the main operating parameters that affect system performance. In particular, the effect of mass flow rate, $\dot{m}$, and of inlet temperature, T_{IN}, were investigated in this work, whereas the other variables were fixed according to values reported in [15] (see Table 1); hourly simulations were performed on a time interval of 8 hours, in order to show the effect of ground thermal saturation in proximity of the borehole wall due to heat exchange with the riser pipe.

Table 1. Operating and geometric parameters of the BHE

Parameter	Value
$\dot{m}$ [kg/s]	var.
T_{IN} [K]	var.
x_{IN}	0.0
H_b [m]	100
D_b [cm]	15.2
D_p [cm]	2.75
δ_p [cm]	0.30
k_p [W/mK]	0.42
k_g [W/mK]	2.60
T_s [K]	283
k_s [W/mK]	1.30
α_s [m^2/s]	0.0561

The inlet temperature must be determined on the basis of the particular application of the GSHP and it is generally in the range 273-280 K. The mass flow rate, instead, must be determined on the basis of the heat capacity and pressure drop values required in the evaporator, generally in the range 0.02-0.2 kg/s for a single BHE.

It is important to note that, in order to work in natural circulation, the fluid pressure drop between the BHE inlet and outlet section, P_{IN} - P_{OUT}, must be negative, in order to have an available pressure head of the fluid in the evaporator of the GSHP. At least, P_{IN} - P_{OUT} can tend to zero, not allowing the fluid flow in the evaporator. The results reported in this work are obtained always in conditions of negative pressure drop, since the model is intended to be coupled to the evaporator model of a GSHP in the case of natural circulation. In this way, the pressure drop required by the evaporator $P_{IN,EV}$ - $P_{OUT,EV}$ can be guaranteed by the pressure difference P_{OUT} - P_{IN} realized in the BHE. In this case, maps of the heat capacity and of the pressure difference can be developed as a function of the operating parameters of the BHE (flow rate, inlet temperature), in order to find the working point that match with the evaporator heat capacity, temperature level and pressure drop, as it will be described in section 3.1.

For a mass flow rate of 0.02 kg/s and an inlet temperature of 273 K, Fig. 2 reports the trend of fluid pressure (a) and temperature (b) along the U-pipe axis when the outlet quality is lower than unity.

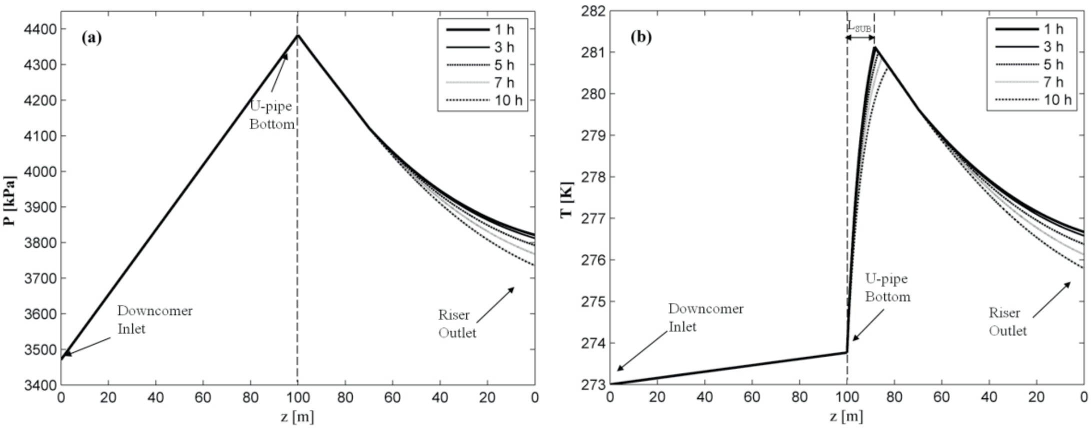

Fig 2. Fluid pressure (a) and temperature (b) along the U-pipe parametric with time. Operating conditions: m = 0.02 kg/s, T_{IN} = 273K

It is possible to observe that the fluid pressure increases along the downcomer, since the gravitational pressure drop term is positive and it overcomes the negative frictional pressure drop term; then, pressure decreases along the riser, due to the decrease of the liquid column height and to the subtractive term of frictional pressure drop. As it is possible to observe, the outlet pressure is higher than the inlet one, due to the presence of the momentum pressure drop in the evaluation of the pressure value along the riser, that tends to increase the pressure along the riser, balancing the effect of the gravitational and frictional terms, therefore allowing to operate the BHE without the use of a circulation pump for the operating parameters investigated.

As regards the trend of the temperature along the U-pipe axis (Fig. 2(b)), it is possible to observe that it slightly increases along the downcomer axis due to the increase of pressure, whereas in the riser it first increases in the subcooling region due to the heat exchange with the borehole, then evaporation starts and the temperature (equal to the saturation temperature at the fluid pressure) slightly decreases in agreement with the pressure trend.

Due to ground thermal saturation in proximity of the borehole wall with passing time, the heat exchange with the ground becomes lower, with a subsequent reduction of the heat power exchanged by CO_2 with the ground that, in turns, gives a lower outlet quality and a lower outlet pressure (due to the reduction of the contribution of the momentum pressure drop), consequently decreasing also the outlet temperature.

By performing a sensitivity analysis, it is possible to obtain the trends of the main outputs as a function of mass flow rate parametric in the inlet temperature after 1 h of operation (Fig. 3). Basically, it is possible to note that an increase of the fluid flow rate leads to an increase of the subcooling length (Fig. 3(a)), up to values equal to half the riser length in the case of the highest T_{IN} (that is, the lowest heat driving force); in agreement with this trend, the outlet quality decreases with increasing the mass flow rate at fixed T_{IN} (Fig. 3(b)), due to a reduction of the residence time in the BHE. As regards the total heat power exchanged by the fluid with the ground, it increases with increasing the mass flow rate (Fig. 3(c)), due to the positive effect of increasing the flow rate on the heat power that overcomes the reduction of x in the range investigated. Consequently to the decreasing trend of x with the flow rate, also the pressure difference between BHE outlet and inlet section decreases with increasing the flow rate (Fig. 3(d)), due to the reduction of the momentum pressure drop contribution, that, at limit, tends to zero with the quality approaching to zero values. The effect of increasing the inlet temperature at a fixed mass flow rate value is to reduce the heat exchange driving force, therefore, increasing the subcooling length and decreasing the heat capacity, the outlet quality and, consequently, the pressure difference.

3.1. Procedure for matching with the evaporator of the GSHP

In order to perform a matching with the evaporator of the GSHP, an example of evaporator heat capacity and pressure drop curves as a function of mass flow rate and inlet temperature were superimposed on the contour maps obtained for the BHE (Fig. 4), in the case of a chevron plate heat exchanger [19].

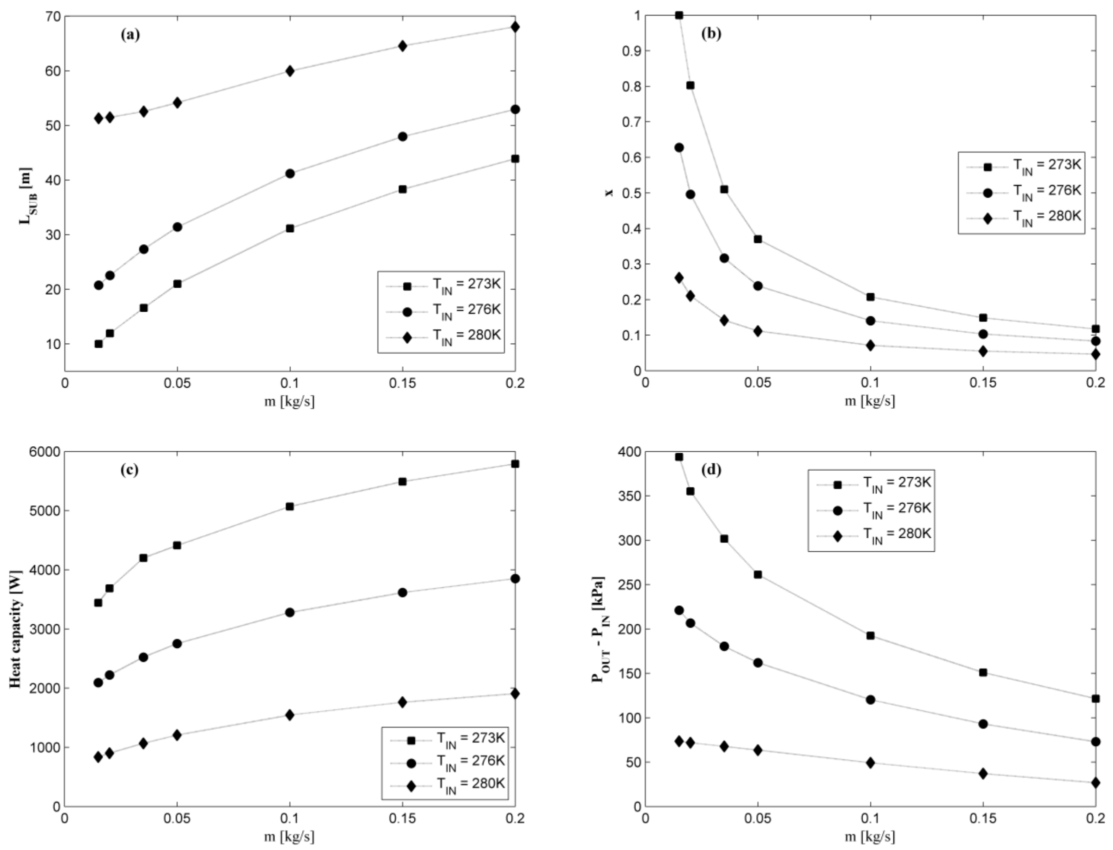

Fig 3. (a) Subcooling length, (b) outlet quality, (c) heat capacity (d) pressure difference between BHE outlet and inlet as a function of mass flow rate m, parametric with the inlet temperature, T_{IN}.

A heat capacity of 4 kW was considered for an evaporation temperature of 269 K, working with R404a. On the heat capacity map (Fig. 4(a)), the heat capacity required by the evaporator, obtained as a polynomial fit curve as a function of the boundary conditions (dotted thick lines), will match with the heat capacity furnished by the BHE (dashed thick lines), identifying a working line (solid line) that gives the couples of inlet temperature and flow rate that give the same heat capacity in the BHE and in the evaporator; the same line can be obtained for the pressure drop, finding the match between the pressure drop required by the evaporator and the pressure difference realized in the BHE for each flow rate and T_{IN} couple (Fig. 4(b)).

By a graphical procedure, it is possible to obtain the working point for the coupled BHE - evaporator system by crossing of the two working lines obtained on the two maps (Fig. 5); in this way, the matching in terms of heat capacity, pressure drop, mass flow rate and temperature level, is performed.

The matching for the system, in this example, is obtained for a CO_2 mass flow rate of 0.053 kg/s and an inlet temperature of 273.5 K. The corresponding heat capacity and pressure drop are 4400 W and 250 kPa, respectively. Therefore, by fitting the data of the evaporator coupled to the BHE, it is possible to find the matching point in the solutions domain by means of a graphical procedure.

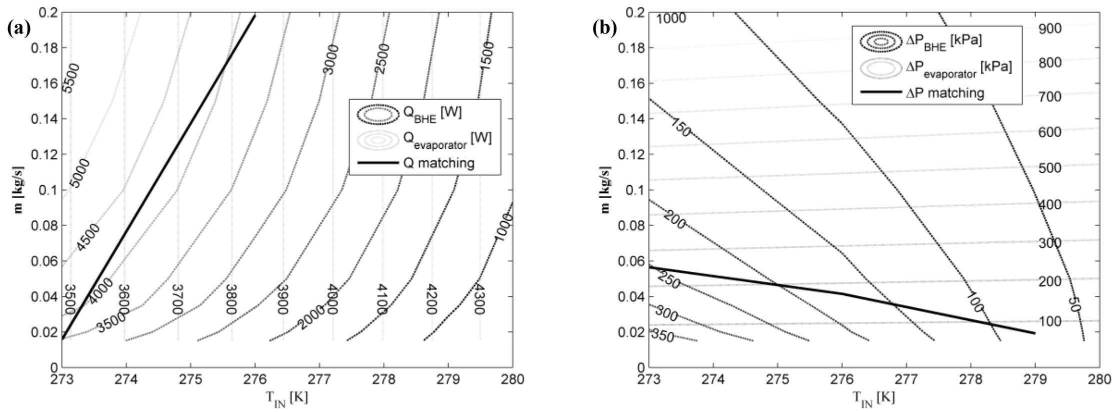

Fig 4. Contour plot for (a) heat capacity and (b) pressure difference between BHE outlet and inlet as a function of mass flow rate, m, and inlet temperature, T_{IN}, coupled to the evaporator curves

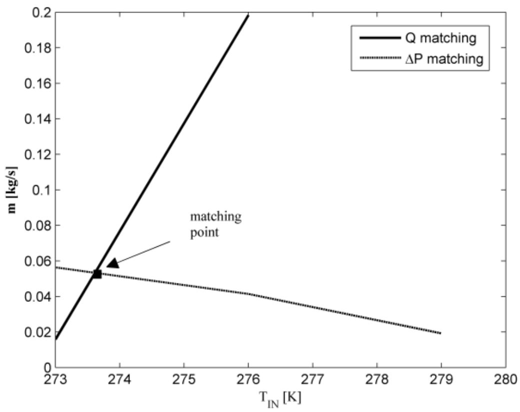

Fig 5. Working point of the system BHE-evaporator in the mass flow rate – inlet temperature domain

4. Conclusions

The work reports the mathematical model of a vertical U-pipe borehole heat exchanger working with carbon dioxide as secondary fluid.

The secondary fluid loop is realized considering an adiabatic downcomer where liquid fluid flows and a riser where heat exchange with the ground leads to fluid evaporation (two-phase loop). The transient nature of the heat conduction problem in proximity of the borehole wall due to soil saturation is considered in the model, therefore a quasi-steady state model is here presented. The model is intended to be coupled to a ground source heat pump model in order to determine the performance of a ground source heat pump working at the evaporator with the carbon dioxide as secondary working fluid, therefore the results on the effect of two main parameters, that is, fluid flow rate and borehole inlet temperature, are investigated. The results show that, in all cases, the CO_2 arrives at the end of the downcomer as a subcooled liquid, due to the gravitational pressure drop that tend to increase pressure with flowing down the downcomer, overcoming the pressure reduction due to the frictional pressure drop. Therefore, a first zone of the riser is dedicated to liquid heating up to the saturation temperature at the riser pressure at a determined borehole abscissa. Over this abscissa value, the evaporation of the fluid starts and the riser is interested by a two-phase flow. The general effect of increasing the fluid flow rate is to decrease the residence time in the system, therefore the outlet quality and temperature decrease, with a decreasing of the pressure difference between the outlet and the inlet section of the borehole heat exchanger. In the range investigated, the system can operate in natural circulation (thermosyphon loop without the employment of an electrically driven pump) since the total pressure difference between the outlet and the inlet is higher than zero. An example of how the borehole model can be coupled to a heat pump model in order to find the operating working point of the entire system was also presented. Since the model takes into account for the transient nature of the heat transfer in the ground, it can be employed for the determination of the seasonal performance of Ground Source Heat Pumps.

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